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PHASE 2 OF THE ARRAY AUTOMATED ASSEMBLY TASK

FOR THE LOW COST SOLAR ARRAY PROJECT

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1. SUMMARY

Various top contact metal systems have been studied. Only Ti Pd Cu approaches baseline (Ti Pd Ag) quality, but this system shows a lack of long term stability. Aluminum back surface field structures have been fabricated and thicknesses of p^+ material of up to 7.0 microns have been achieved with open circuit voltages of 0.59V. A general purpose ultrasonic welder has been purchased and tests using various metal foils are under way. During fabrication of the demonstration module, several cells became cracked. Due to redundancy of interconnections, the module was not open circuited but the efficiency was reduced to 8.8%. The broken cell was interconnected with a strap across the back and the efficiency was increased to 11.5%. A cost analysis (SAMICS) was made using a process sequence developed during Phase 1 of this contract. The results indicate a selling price of \$0.56/watt peak (in 1986 with 1975 dollars).

2. INTRODUCTION

The major objective of this program is to define and verify a process sequence for the fabrication of solar cell modules from dendritic web silicon. Low manufacturing costs are required for each process step if the target selling price of \$0.50/peak watt (1975 \$ in 1986) is to be met.

The process sequence we have developed has been separated into five major processes and 44 sub-processes, with the capital, labor, utilities and commodities requirement for each sub-process determined. These data are input to the SAMICS program to determine module selling price.

The process sequence uses the concept of parallel processing of a number of long lengths of web, with a total throughput of $0.5 \text{ m}^2/\text{operating minute}$. We have considered a processing line having a capacity of 25 MW/yr which is an effective size from a cost standpoint. This calculation gave a module selling price in 1986 of \$0.56/peak watt (1975 \$).

We have also determined costs and module selling prices for a pilot facility operating in 1984 and having the capacity of 2 MW/year. The module selling price in 1984 was \$1.40/peak watt (1975 \$).

This same processing sequence has been used to cost a manufacturing technique where a continuous length of web is processed throughout the sequence. In this case, the selling price was \$0.50/peak watt in 1986 (1975 \$) including an assumed cost of \$.17/peak watt for the dendritic web silicon input to the line.

In the process sequence discussed above, several process steps required further definition and development. These were the front and back contact metallization system, the back surface field formation, and the cell interconnection.

In the cost analysis of our process sequence it was shown that silver in the electroplated Ti Pd Ag contact system costs about 1¢ per watt. We have investigated the use of electroplated Cu as a substitute for the Ag, and have also studied the Pd Cu system to determine if the barrier metal Ti can be omitted from the system. The substitution of Cu for Ag would have several advantages. First, the material cost of the top contact system would be greatly reduced. Second, by using a copper foil interconnect strap, a copper-copper contact could be achieved for the front surface and thus reduce galvanic corrosion problems. The omission of the evaporated Ti would make a simpler contact system.

The Ti Pd Cu contact system has properties equal to that of the Ti Pd Ag system, even withstanding initial sintering to 400°C. However, initial tests suggest that it does not have long term stability. This is believed to be the result of the diffusion of Cu through the Ti Pd

to decrease the minority carrier lifetime. Thus Ti Pd does not serve as a barrier for the fast diffusing Cu. Experiments were also carried out to determine the stability of thicker layers of Pd (both sintered and unsintered) in combination with electroplated Cu. This system also failed with further heat treatment, again due to Cu diffusion. Therefore, at this time the Ti Pd Ag system is the only contact metallization tested which is capable of withstanding high temperature aging, and therefore, the most suitable for long term stability under operating conditions.

Several techniques were tested in an attempt to improve the back surface field produced by boron diffusion. These included a deep and shallow diffusion with BBr_3 and a deep diffusion using a doped boron oxide film. None of these techniques were significantly better than the other two, with the maximum V_{oc} obtained (on web) of 0.57V. (This represents an enhancement due to the BSF of 0.050V.) Based on these results and the known V_{oc} enhancement obtainable with Al back surface fields, studies have been initiated in this area. In the initial experiments, the difference in Al BSF profiles resulting from different surface conditions are being studied. A maximum V_{oc} of 0.591V has been obtained with Al evaporated on both a p-type Si surface as well as on a shallow n^+ surface. In these cases, the Al was alloyed in at 850°C using rf heating. Further work will emphasize other methods for applying the Al.

In the defined process sequence, the interconnection between cells is accomplished using ultrasonic welding techniques to bond thin metallic foils to the contact metallization.

Bonding between two metals can occur when the surfaces are scrubbed against each other at ultrasonic frequencies. Although the mechanism that effects the bonding is not known, it is hypothesized that the surface contaminants are removed and atomic contact between clean metals is achieved, or that the scrubbing action causes microfractures in the materials which form strong, interlocking bonds. Our studies have shown it is possible to interconnect Cu and Al foils to evaporated Al and Ag and electroplated Cu and Ag. The method appears to be feasible and suitable for automation. Long term reliability studies have not been made.

In the last quarter of Phase 1 of this contract, a demonstration module was fabricated using 1.6×7.0 cm dendritic web silicon solar cells. The module area was 834.6 cm^2 with a cell area of 806.1 cm^2 . During the final stages of the packaging one cell was badly cracked. Since all 72 cells were in series this cell reduced the total output of the module and limited the efficiency to 8.8%.

This module was repaired by soldering a connecting strap across the back of the one cell that appeared to be most responsible for the current limitation, and therefore for the low efficiency. After this repair, the module was remeasured both at the Westinghouse R&D Center and at NASA Lewis Research Center. In both cases the efficiency was 11.5%.

There are still several cells in the module which are cracked which limit the current. Thus it may be assumed that if all cells were perfect, the module efficiency should exceed 12% as this represents the minimum efficiency of the cells used.

3. TECHNICAL RESULTS

3.1 Metallization

It was previously reported (4th Quarterly and Annual Report, this contract) that the Ti Pd electroplated copper system showed great promise in that it behaved the same way as the Ti Pd electroplated Ag system, even when sintered to 400°C . This work has been continued by studying the long term stability of the Ti Pd Cu system and the behavior of the evaporated Pd electroplated Cu system.

To test the stability of the Ti Pd Cu system an accelerated test was carried out where two samples having Ti Pd Cu contacts were heated at 230°C in N_2 for times to 100 hours. Two control cells with Ti Pd Ag contacts were also tested. Table 1 shows the results of this test. After 25 hours at 230°C , there was no significant change in any of the parameters. However, after 100 hours, the short circuit current and efficiency of the Ti Pd Cu samples were considerably degraded. Dark I-V measurements made on these samples showed that neither the series resistance or shunt resistance had changed, and that the degradation was due to an

TABLE I

TEST FOR STABILITY OF Ti Pd Cu CONTACT SYSTEM

Test Conditions	I _{sc} (mA)		V _{oc} (V)		EFF (%)	
	Ti Pd Ag	Ti Pd Cu	Ti Pd Ag	Ti Pd Cu	Ti Pd Ag	Ti Pd Cu
As	22.7	20.4	.545	.544	9.1	8.4
Fabricated #2	17.9	21.4	.472	.556	6.2	8.8
25 Hrs.	21.8	20.4	.550	.558	9.0	8.5
230°C	17.6	21.5	.479	.545	6.2	8.8
100 Hrs.	21.9	17.5	.551	.516	9.0	6.5
230°C	17.7	15.4	.478	.511	6.2	5.0

increase in the excess junction current and a decrease in the lifetime. Thus, it would appear that the Ti Pd did not serve as a barrier for the fast diffusing Cu. (In the earlier reports we showed that the Cu and Pd Cu contacts degraded the cell performance in the same manner.)

During the annealing cycle, the cells with Ti Pd Ag contacts showed no significant change. Although not noted in the table, the Ti Pd Ag contacted cells were annealed for an additional 100 hrs. without any change.

Thus from these data we conclude that Ti Pd (total thickness $\approx 600 \text{ \AA}$) does not serve as a barrier for Cu at 230°C . Extrapolating high temperature diffusion data, the above results indicate that a Ti Pd Cu contact system may not have a 20 year lifetime under normal operating conditions, with a maximum temperature of 100°C .

As noted earlier, the Pd Cu contact system would not withstand sintering above 150°C . Further experiments were carried out investigating the effect of (1) thicker Pd layers and (2) the effect of sintering the Pd before Cu plating to form Pd silicides.

In these experiments, $800 \text{ \AA}$ and $3000 \text{ \AA}$ of Pd were evaporated on the sun side of the cell and $4 \text{ \mu m}$ of Cu was plated on the Pd. The data on these samples is shown in Table 2 in the unsintered column. In this table, η , I_{sc} , V_{oc} and FF have their normal meaning. R_s is the cell series resistance, R_{SH} the shunt resistance and I_j is the excess junction current measured at 0.3V . From the unsintered data, there is no indication of any difference from a baseline contact system. These samples were then sintered at 300°C for 15 min. in N_2 . As seen in Table 2, this process degrades the cells considerably, mainly by a 2-3 order of magnitude increase in the excess junction current (R_{SH} is nearly constant). It thus appears that unsintered Pd is unable to form a barrier for Cu diffusion, even at $3000 \text{ \AA}$ thickness.

Table 2
EVAPORATED Pd - PLATED Cu CONTACTS

	800Å Pd + 4 μm Cu		2000Å Pd + 4 μm Cu	
	Unsintered	Sintered	Unsintered	Sintered
$\eta(\%)$	8.96	4.67	9.15	3.0
$I_{sc}(\text{mA})$	21.5	20.9	21	21
$V_{oc}(\text{V})$	0.542	0.501	0.552	0.360
FF	0.727	0.426	0.746	0.4
$R_s(\Omega)$	0.8	0.4	0.6	0.3
$R_{sh} _{-1V}(\text{K}\Omega)$	40	40	33	30
$I_j _{.3V}(\text{mA})$	0.01	5.67	0.082	14

- . Sintering was done at 300°C for 15 min. in N_2 .
- . Sintering degrades the junction response severely.
- . It appears that unsintered Pd is unable to form a barrier for Cu diffusion regardless of Pd thickness.

In the next experiment, the layers of Pd (again 800 Å and 3000 Å) thick were sintered at 300°C for 15 min. in N₂ to form Pd silicides. After this treatment, 4 µm of Cu was electroplated on the surface. This data is shown in Table 3. Also seen in Table 3 are the results when the Pd Cu system is sintered at 300°C. Again, there is severe degradation due to an increase in the junction excess current. The conclusions that can be drawn from this data is that Pd sintered at 300°C does not form a barrier for Cu diffusion. (The degradation noted is due to Cu and not Pd because the cells with Pd only were measured and showed a very low junction excess current.)

These data show that the Pd Cu system is even more sensitive to heat treatment than the Ti Pd Cu system, and thus Ti is required as a barrier metal.

3.2 Back Surface Field Studies (BSF)

3.2.1 General Background

The presence of a high-low junction near the back surface of an n⁺p junction structure results in enhanced open circuit voltage and short circuit current. The higher V_{oc} of the BSF cells is due to the reduced back surface recombination velocity and a built-in voltage in the p⁺p region. The built-in field in the high-low junction reduces the loss of photogenerated carriers and enhances the quantum efficiency of the base region of the BSF cell result in higher I_{sc}.

The above effects can be summed up in the expression for the junction leakage velocity (Spp⁺) of minority carriers across the p⁺p depletion region given by^{1,2,3}:

Table 3
SINTERED Pd - PLATED Cu CONTACTS

	800Å Pd Sintered at 150°C 4 μm Cu		3000Å Pd Sintered at 300°C 4 μm Cu	
	Unsintered	Sintered	Unsintered	Sintered
η (%)	8.77	4.62	8.71	2.46
I_{sc} (mA)	20.4	20.4	20.9	18.5
V_{oc} (V)	0.538	0.488	0.543	0.298
FF	0.755	0.458	0.725	0.42
R_s (Ω)	1.5	0.46	0.8	0.3
$R_{sh} _{-1V}$ (K Ω)	100	60	250	10
$I_j _{.3V}$ (mA)	0.019	4.5	0.038	11

- . Sintering was done at 300°C for 15 min. in N₂.
- . Sintering the heat treated Pd-Plated Cu contacts severely degrades the junction response.
- . Pd sintered to 300°C does not serve as a barrier for Cu diffusion.
- . Degradation is related to Cu and not to Pd because Pd sintered alone at 300°C gives good cells.

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$$S_{pp}^+ = \frac{D_{p+}}{L_{p+}} \coth \left(\frac{W_{p+}}{L_{p+}} \right) \frac{N_A}{N_{A+}} \exp [\Delta E_g / kT]$$

where: D_{p+} = electron diffusion constant in p+ region
 L_{p+} = electron diffusion length in p+ region
 W_{p+} = width of p+ region
 N_A = acceptor concentration in p region
 N_{A+} = acceptor concentration in p+ region
and $\frac{\Delta E_g}{kT}$ is a band gap narrowing term in the heavily doped p⁺ region, which increases with the p⁺ doping.

As the value of S_{pp}^+ approaches a minimum, the effective bulk lifetime in the p region increases and the enhancement of the cell parameters discussed above occurs.

Based on this equation, certain material and device parameters which will cause S_{pp}^+ to be a minimum can be identified. First, the minority carrier diffusion length in the p+ region, L_{p+} , should be as large as possible. Although no direct measurements have been made on the magnitude of L_{p+} , Hauser and Dunbar⁴ suggest that it varies from a few tenths of a micron at $N_{A+} = 10^{21}/\text{cm}^3$ to several microns at $N_{A+} = 10^{18}/\text{cm}^3$. Second, the ratio of W_{p+}/L_{p+} should be at least equal to three since the $\coth \theta$ approaches a constant minimum value of 1 for $\theta = 3$. Third, the ratio of N_A/N_{A+} should be small. Since N_A in itself must be near $10^{15}/\text{cm}^3$ so that an efficient n⁺p junction can be fabricated, the value of N_{A+} should be large. There is an obvious trade off here because as N_{A+} increases L_{p+} decreases and ΔE_g increases. Sinha and Chattopadhyaya have shown that for a 5 μm p+ region and an N_A of $10^{15}/\text{cm}^3$, the surface leakage velocity first decreases because of the increase in the ratio of N_A/N_{A+} , but beyond $N_{A+} \approx 2 \times 10^{19}/\text{cm}^3$ S_{pp}^+ begins to increase due to the band gap narrowing effect.

In light of this information and discussion, we should consider the characteristics of boron doped and Al doped BSF to determine which is preferable for high efficiency solar cells. Table 4 lists some of these parameters.

TABLE 4
COMPARISON OF B AND Al DOPED BACK SURFACE FIELDS

	B-doped	Al-doped
N_{A+} ($\#/cm^3$)	10^{21}	5×10^{18}
L_{p+} (μm)	few tenths μm	several μm
W_{p+} (μm) obtainable	1-2	> 10

From the above data, it is obvious that $W_{p+}/L_{p+} > 3$ can be satisfied for both B and Al BSF. S_{pp+} should be lower for Al BSF because $L_{p+}(Al)$ is an order of magnitude greater than $L_{p+}(B)$. Also, S_{pp+} should be high for boron BSF because of band gap narrowing offsetting the benefit of the high N_A/N_{A+} ratio.

Considering all these factors, Sinha and Chattopadhyaya⁽²⁾ suggest that S_{pp+} will be a minimum for $10^{19}/cm^3$ to $10^{20}/cm^3$. This indicates that to a first approximation that Al back surface field may be preferable.

Thus, in the past quarter we have initiated a study of techniques for forming Al BSF's as well as completing a boron BSF study.

3.2.2 Boron Diffused Back Surface Fields

Earlier in the program, experiments indicated that boron doped back surface with either a BBr_3 diffusion source or a boron doped CVD oxide was essentially equivalent. To extend and verify this data, a diffusion experiment was carried out with four different web crystals and a float zone Si baseline which were diffused using three different techniques (BBr_3 for a 0.4 μm junction; BBr_3 for a 1 μm junction and B-doped CVD oxide for a 1 μm junction). This experiment should determine if boron

diffused BSF's could be improved either by deeper junctions or with the doped oxide source. The data is shown in Table 5. In this test, the cells were all processed in the same manner except for the boron diffusion technique.

From the data it is seen that V_{oc} does not systematically increase with increasing junction depth (w_{p+}), therefore while the condition of $w_{p+}/L_{p+} > 3$ is probably satisfied, the band gap narrowing effect is offsetting the favorable N_A/N_{A+} ratio.

Based on these data, and the advantages of the Al doped BSF, all BSF effort is now concentrated on Al alloying.

3.2.3 Aluminum Back Surface Field Studies

These experiments are concerned with the formation of back surface fields by alloying an Al layer into the back surface of a solar cell structure. This procedure can be described as follows: a known thickness of Al is deposited on the back surface of the cell structure; the thickness of Al required is determined by the desired final p^+ junction depth and the alloying temperature. During the firing (generally 800°C - 850°C) a hyper-eutectic Al-Si alloy is formed, with the amount of Si dissolved being a function of the initial Al thickness and the temperature. During the cooling cycle, Al doped Si from the hyper-eutectic grows epitaxially from the alloy-Si interface toward the back of the crystal. When the eutectic temperature is reached ($\approx 570^\circ\text{C}$) the Al-Si eutectic freezes out on the regrown epitaxial layer. This regrown silicon is doped with Al to about $3-8 \times 10^{18}/\text{cm}^3$ and forms an abrupt and fairly deep p^+p junction and an n^+pp^+ cell structure.

We are studying the BSF formation using the following approach.

1. Effect of back surface condition on Al alloying (p or n type back surface).
2. Methods of applying Al to back surface, (evaporation, silk screening or painting).

Table 5
 Boron Diffused - Back Surface Fields
 (Measured at AM-1; AR Coated - 1.4 Enhancement)

Crystal #	BBr ₃ (X _J ≈ 0.4 μm)	BBr ₃ (X _J ≈ 1.0 μm)	Boron Oxide (X _J ≈ 1.0 μm)
<u>EFFICIENCY</u>			
RE50-1.2	13.0	12.4	--
RE54-1.2	14.1	14.7	14.3
RE54-2.1	12.8	12.3	13.3
J80-5.1	10.9	10.4	9.0
Float Zone } Si Baseline }	14.7	--	14.8
<u>I_{sc} (mA)</u>			
RE50-1.2	30.9	30.8	--
RE54-1.2	32.2	32.6	32.6
RE54-2.1	30.9	30.9	31.6
J80-5.1	28.2	30.0	30.9
Float Zone } Si Baseline }	31.8	--	32.4
<u>V_{oc} (V)</u>			
RE50-1.2	.547	.533	--
RE54-1.2	.570	.573	.566
RE54-2.1	.538	.526	.551
J80-5.1	.507	.516	.535
Float Zone } Si Baseline }	.580	--	.570
<u>τ_{OCD} (μsec)</u>			
RE50-1.2	12	8	--
RE54-1.2	35	34	35
RE54-2.1	12	7	22
J80-5.1	2	3	5
Float Zone } Si Baseline }	35	--	13

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TABLE 6
Al BSF Cells - 9.6 μ m Evaporated Al - RF Heated
(AM1 - AR Coated)

	I_{sc} (mA) (No BSF)	V_{oc} (V)	FF	EFF(%)	τ_{OCD} (μ sec)
CZ Cells	30.8	.543	.762	13.45	6
BSF - (Al Evaporated on n skin)					
CZ Cells	31.4	.591	.769	15.1	36
WEB Cells	31.5	.576	.750	14.4	43
BSF (Al Evaporated on p-type surface after n-type etched off)					
CZ Cells	30.4	.591	.764	14.5	29
WEB Cells	31.0	.572	.768	14.5	40

on a Si coated carbon susceptor and heated to 820°C in 5 minutes held for 15 seconds then cooled by turning off power. Cells were made from these samples and compared with non-BSF cells, i.e. n^+p structures. These data are shown in Table 6 and are averages of a number of cells.

The p^+p junction profiles of representative cells are shown in Figs. 1 and 2. Figure 1 is the concentration profile of a float zone silicon where the Al was evaporated on a n^+ layer, (remaining from a phosphorous diffusion). In this case the Al was alloyed through the n^+ layer to form the p^+p structure.

Figure 2 is the concentration profile of a float zone silicon cell where the Al was evaporated on a p-type surface (n^+ surface etched off).

3. Method of heating for alloying (rf or resistance heated furnaces).

The quality of the BSF region is being evaluated by measuring the p^+p junction profile and the cell parameters, specifically V_{oc} .

At this point, data is available only on evaporated Al, alloyed on an rf heated susceptor in H_2 .

In this series of experiments, 9.6 μm of Al was evaporated on the back of the cell structure.

These cells used in these preliminary tests had been diffused in phosphorous before the Al deposition to form an n^+p junction structure. During this diffusion, some phosphorous also diffused into the back of the wafer leaving an n^+ skin. In one case, this n^+ layer was removed by etching before the Al deposition, while in the other case the Al was evaporated directly on this n^+ layer. The samples were placed on a Si coated carbon susceptor and heated to 820°C in 5 minutes held for 15 seconds then cooled by turning off power. Cells were made from these samples and compared with non-BSF cells, i.e. n^+p structures. These data are shown in Table 6 and are averages of a number of cells.

The p^+p junction profiles of representative cells are shown in Figs. 1 and 2. Figure 1 is the concentration profile of a float zone silicon where the Al was evaporated on a n^+ layer, (remaining from a phosphorous diffusion). In This case the Al was alloyed through the n^+ layer to form the p^+p structure.

Figure 2 is the concentration profile of a float zone silicon cell where the Al was evaporated on a p-type surface (n^+ surface etched off).

Figure 1
Float Zone Silicon
Al Evaporated on n⁺ Surface

$$X_j = 6.2 \mu\text{m}$$

$$\eta = 15.1\%$$

$$\tau_{\text{OCD}} = 33 \mu\text{sec}$$

(AM-1, AR Coated)

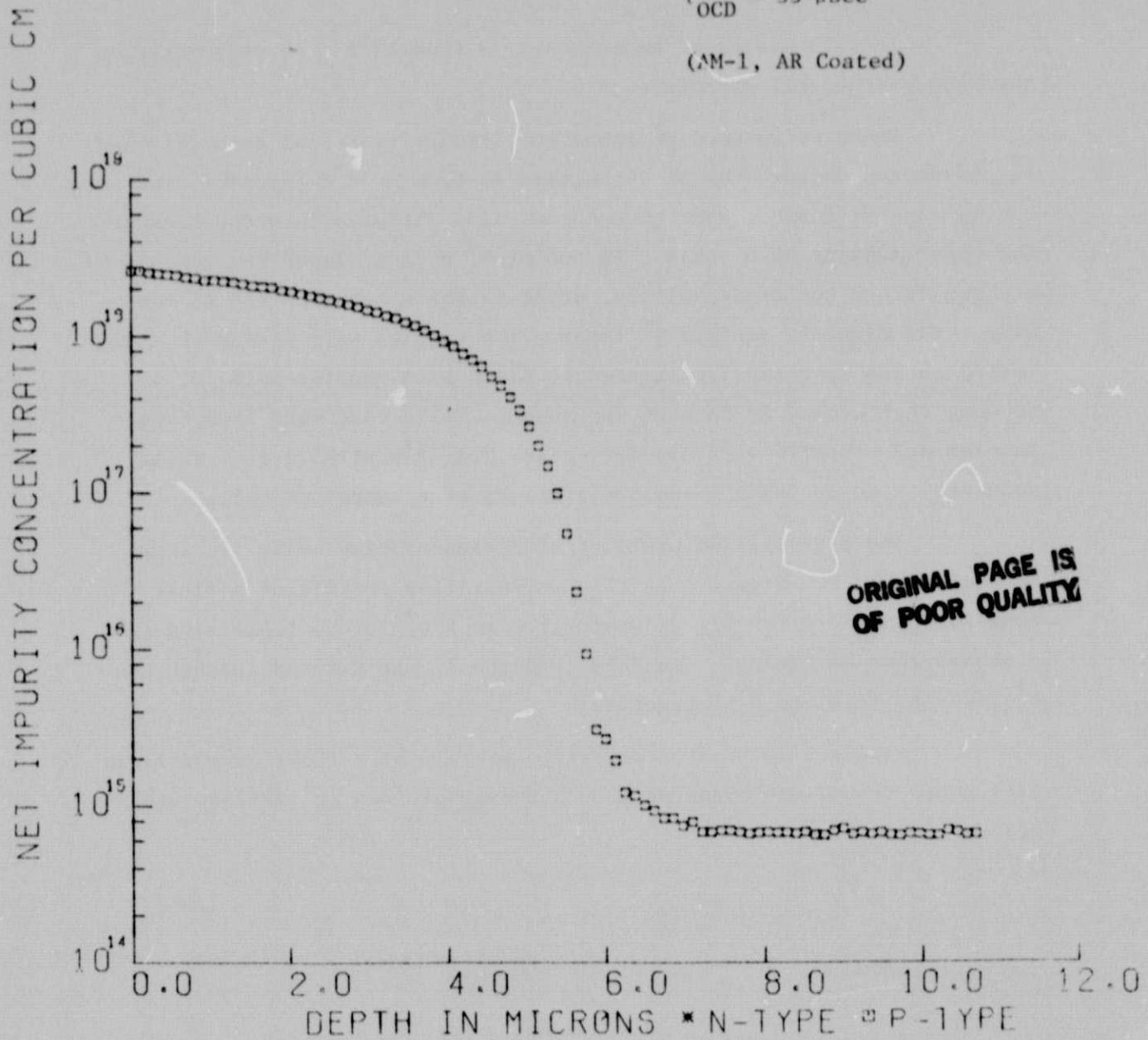
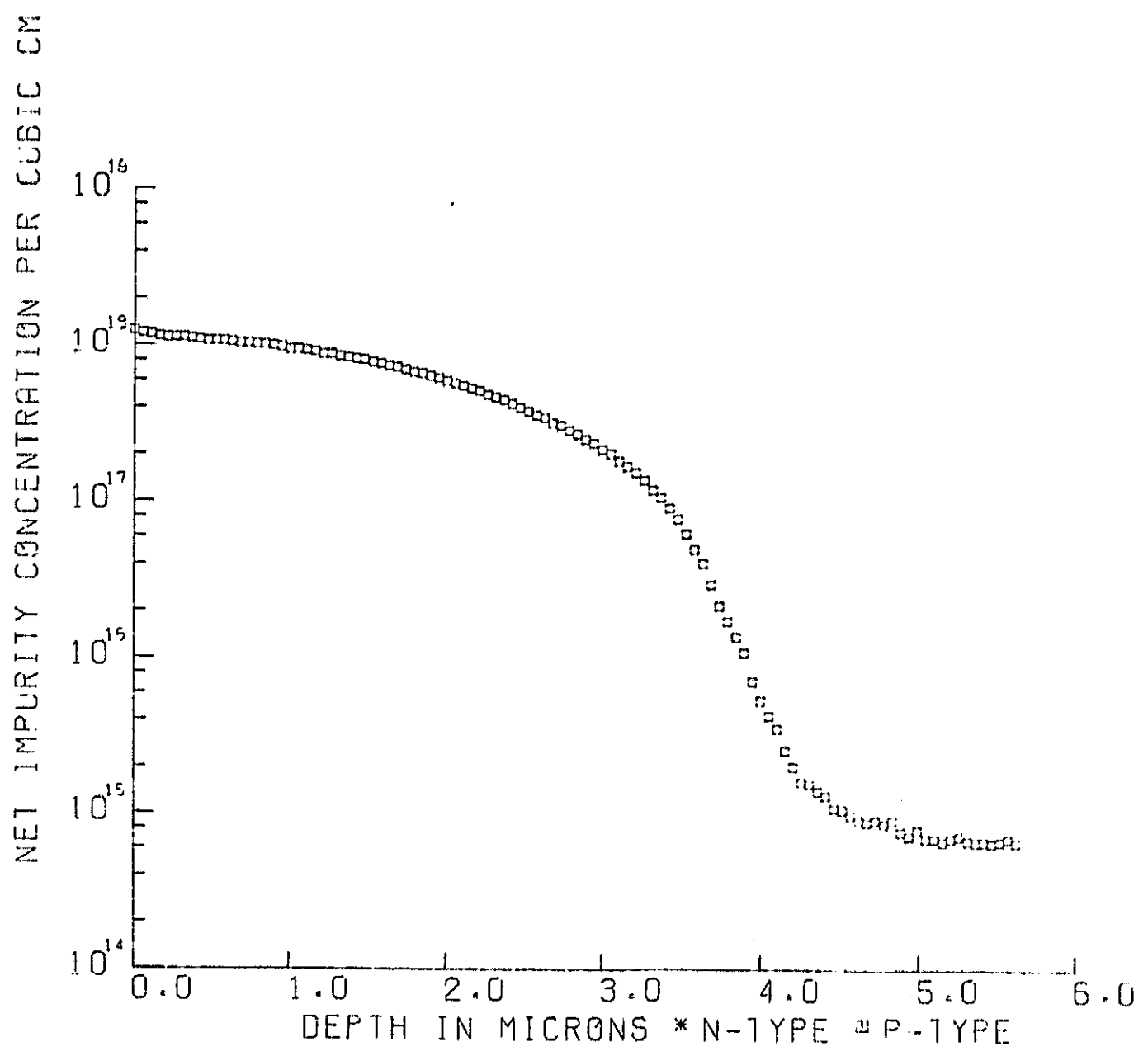


Figure 2
Float Zone Silicon Cell
Al Evaporated on p⁺ Type Surface

$X_j = 4.5 \mu\text{m}$
 $\eta = 14.6\%$
 $\tau_{\text{OCD}} = 30 \mu\text{sec}$
(AM-1, AR Coated)



Several comments can be made regarding this preliminary data.

- The junction depth in the two samples (4-6 μm) approaches the 8-10 μm believed to be required for optimum BSF operation.
- There is an enhancement of about 50 mV due to the Al BSF (Cf FZ BSF and no BSF).
- The fact that the dendritic web does not show as large enhancement as the FZ silicon is believed to be due to a more shallow p^+ junction in the web.
- There appears to be some advantage in driving the Al through the n^+ skin, but the difference is so small that this conclusion necessitates confirmation.

During the course of these experiments, it was noted that the Al did not always alloy in smoothly. In these cases, the Al would form balls on the surface and alloy in from these balls, giving a non-uniform penetration. Investigations are being conducted to determine if this is due to surface preparation, or a thermal effect such as rise time of the heating, or final temperature.

In any event, this technique appears feasible for forming BSF cells.

3.3 Cell Interconnections

Bonding between two materials can be made to take place when the material surfaces are scrubbed against each other at ultrasonic frequencies. The detailed method by which the bonding takes place is not known in all cases. When thermo-plastic materials are bonded, the scrubbing action appears to generate sufficient heat that local melting of the surfaces occurs. When metals are joined, it is less likely that melting occurs; instead, it is hypothesized that either (1) surface oxides and contaminants are abrasively removed and atomic contact between clean metals is achieved, which in turn leads to chemical bonding or (2) the scrubbing action causes microfractures in the surfaces of the metals and these fractures interlock forming a strong metal-to-metal bond.

Whatever the exact mechanism of ultrasonic bonding between metals, the process is successful in applications ranging from joining large copper busbars onto electric motor alternators to attaching fine wires to thin films on integrated circuits.

Because the exact nature of the bonding process is not known, the achievement of acceptable ultrasonic bonds is largely an empirical process. A large number of parameters determine the quality of an ultrasonic bond. In so far as the materials are concerned, the thickness, temper, surface condition and the materials themselves are important. Among the bonding parameters are the ultrasonic frequency, the vibrational amplitude, the size and shape of the tool, the tool material, the vibrational power input, the clamping force between the tool and the work piece, and the length of the time interval during which power is applied. It has also been shown that the properties of all the materials beneath the work piece have an effect. The large number of variables makes it very likely, once the materials to be joined have been chosen, that some combination of the other variables will result in good ultrasonic bonds.

Ultrasonic bonding machines are of two basic types. The simplest type--the spot bonder, is one in which the ultrasonically driven tool contacts the materials to be joined in a single area. After a bond is made, the tool is lifted and repositioned in preparation for the next bond. An analysis of this operation shows that the throughput rate of bonds is limited by the time required to reposition the tool between bonding operations. In the second type of machine, commonly called a seam bonder, the ultrasonically driven tool is in the shape of a wheel which is made to roll across the workpiece, making a continuous linear bond. This type of machine is widely used to splice the ends of metal foils and plastic sheets. The advantages of applying this type of machine to solar cell interconnection are obvious if the interconnect material is in the form of a continuous tape or web to be bonded along one edge of a solar cell. Even if the interconnect is in the form of discrete tabs bonded at points one centimeter apart, the use of a seam

welder type of machine will result in increased bonding speed: a spot bonder can bond and position itself for another bond at a rate of about one bond per second; a seam welder can roll along a solar cell edge (or along a long line of solar cells) at a rate of 15 cm/sec, making 15 bonds per second.

For the reasons given above, Westinghouse has proposed that for the Automated Array Assembly Task, solar cell interconnection should be accomplished with thin metal foils (e.g. aluminum or copper) ultrasonically bonded to solar cell metallization.

An experimental survey of materials and bonding parameters was undertaken. The purposes of this investigation were to (1) demonstrate the applicability of ultrasonic bonding to thin dendritic web solar cells and (2) to gain practical information on possible materials, process parameters, and bond characteristics.

The machine used in this investigation was a Sonobond (West Chester, PA) ML-6010 (W-1060D) spot bonder with a .062" diam tool having an spherical tip with a two inch radius. This machine operates at a frequency of 60 kHz and has a maximum power output of 10W.

Interconnect materials were aluminum (.002", .001", 0.0005", and .0003" thickness), brass (.002" and .001" thickness), and copper (.002" and .0015" thickness). Solar cell metallizations used were 4 μ m thick silver (electroplated and vacuum evaporated), 4 μ m thick electroplated copper, and 500 nm thick vacuum evaporated aluminum.

For the purposes of this survey, the bonding parameters were (a) tool force: 30, 150, 500, 700, and 1100 gm; dwell time: .028 and .044 sec; (c) power input: 0.36, 3.7, and 10.2W. No special cleaning or surface preparation of the bonding materials was used. Those material combinations which produced good and poor bonds under the above bonding conditions are summarized in Table 7. It must be emphasized that those combinations which made poor bonds under these conditions might be expected to produce good bonds under different conditions.

TABLE 7

Material Combinations Producing Good (G) and Poor (P)
Ultrasonic Bonds under a Limited Number of Bonding Conditions

Cell Metallization Interconnect Material	4 μ m Electroplated Silver	4 μ m Vacuum Evaporated Silver	500 nm Vacuum Evaporated Aluminum	4 μ m Electroplated Copper
.002" aluminum	G	G	G	G
.001 aluminum	G	G	G	G
.0005 aluminum	G	G	G	G
.0003 aluminum	G	G	G	G
.002" brass	P	P	P	P
.001 brass	G	G	P	G
.002 copper	P	P	P	P
.0015 copper	P	P	G	G

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It is essential that interconnect bonds have low electrical resistance. The contact resistances of those bonds labelled as good (G) in Table 7 were measured using a 4 point probe technique. All of these bonds exhibited contact resistance of less than one milliohm and a specific resistance of less than $10^6 \Omega \text{ cm}^2$. Since the bonded area was quite small (about .010" diam) because of the shape of the bonding tool, this figure must be regarded as a very good one.

A limited number of pull tests were performed to demonstrate the mechanical strength of ultrasonic bonds. Even for the small bonded areas achieved in this investigation, the bond strengths were adequate for cell handling prior to encapsulation. Bond strengths are shown in Table 8 for several interconnect-metallization combinations.

From the above data, we conclude that when proper processing parameters are used, low resistance, strong bonds can be made between a variety of metal foils and solar cell metallizations. The bonding process has no adverse effect upon cell characteristics.

The work described above was carried out at the Sono-Bond Development Laboratory by Westinghouse personnel.

To further optimize this process and obtain capability for using ultrasonic welding in the fabrication of further modules, a general purpose welder was purchased. The required jigs and fixtures are now being fabricated, and weld tests will begin shortly.

3.4 Demonstration Panel

During this quarter the fabrication and evaluation of a demonstration module was completed. The module was composed of 72 cells, each being 1.6 cm x 7.0 cm. The cells were series connected with a total cell area of 806.4 cm^2 .

TABLE 8

45° Pull Strength Tests of Ultrasonically Bonded Interconnects
[Strength in grams (force)]

Cell Metallization Interconnect Material	4 μ m Silver	4 μ m Copper	500 nm Aluminum
.002" aluminum	72 - 90	—	60 - 100
.001" aluminum	30 - 70	—	—
.0005" aluminum	5 - 30	—	—
.0003" aluminum	9 - 30	—	—
.002" brass	—	25 - 50	—
.001" brass	90 - 140	9 - 20	—
.002" copper	Weak	14 - 50	—
.0015" copper	54 - 150	60 - 95	32 - 40

The cells were mounted in an Al plate (6.4 mm thick), which had been milled out to form a recess, with a 0.7 mm lip around the edge. The Al plate was 28.45 cm x 29.34 cm or a total area of 834.6 cm². With 72 cells mounted on the plate, the cell area/substrate area packing factor was 97%.

The cells (examples are shown in Fig. 3) were interconnected by soldering silver plated copper foil straps to the seven silver plated contact pads on the front of each cell to the evaporated silver on the back of the cell.*

Table 9 shows the properties of 81 cells which were originally chosen for fabricating into the module. These cells had efficiencies from 12.0% to 14.2% and were from a number of web growth runs fabricated in different processing runs. During the fabrication process nine cells were broken.

To fabricate the module, four strips of interconnected cells (18 cells per strip) were made up. To fit into the Al plate, the spacing between the cells was held to 0.025 cm or less. A shallow layer of silicone encapsulant** was then poured into the milled-out Al plate and the strips of cells placed (sun side up) into the recess. The spacing between the strips of cells was held to 0.03 cm or less. The plan was to partially cure the silicone and then reposition the cells to assure no shorting occurred and make the final interconnects between the strips of cells. To effect this partial cure, the module was placed in a warm oven (90°C) and evacuated to remove any remaining bubbles from the out-gassed silicone. However, this combination of vacuum and temperature enhanced the polymerization rate and after 10 minutes the silicone was fully cured. Thus, no repositioning of the cells was possible. In this condition there were no cells shorting out; however, one or two of the cells were "shingled" so that a small portion was above the lip of the Al plate.

* Soldering techniques were used since the ultrasonic welding method is not fully developed.

** General Electric Company RTV-615.

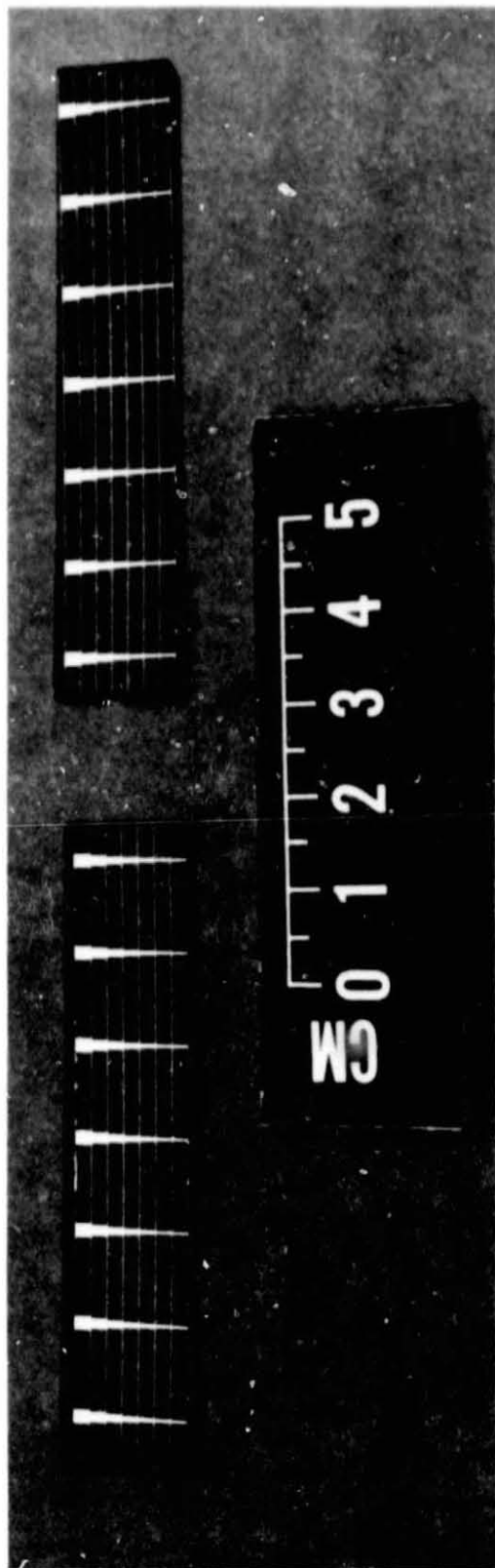


Figure 3. Solar Cells of 1.6 cm x 7.0 cm dimensions which have been laser scribed from dendritic web silicon.

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TABLE 9

Cells Used in Demonstration Panel

Cell #	I_{sc} (mA)	V_{oc} (V)	I_p (mA)	FF	Eff. (%)	τ_{ocd} (usec)
1	294	.556	275	.765	12.2	3.9
2	301	.543	281	.768	12.2	5.2
3	308	.555	287	.764	12.7	5.2
4	312	.580	287	.752	13.3	16.9
5	296	.557	277	.759	12.2	5.2
6	301	.565	281	.765	12.7	10.7
7	309	.548	288	.768	12.7	7.8
8	305	.563	283	.759	12.7	3.9
9	302	.554	282	.764	12.5	5.9
10	304	.550	283	.765	12.5	8.5
11	311	.556	286	.740	12.5	10.8
12	311	.564	291	.767	13.1	5.5
13	295	.539	276	.775	12.0	3.6
14	312	.538	291	.759	12.4	6.5
15	310	.558	293	.792	13.4	5.2
16	314	.578	292	.763	13.5	15.6
17	320	.560	296	.748	13.1	10.4
18	314	.549	290	.757	12.7	9.1
19	315	.566	296	.734	12.8	11.7
20	300	.544	280	.765	12.2	4.9
21	305	.540	280	.767	12.1	5.5
22	320	.577	297	.761	13.7	14.3
23	312	.577	289	.760	13.3	7.8
24	311	.559	288	.732	12.4	18.2
25	298	.554	279	.768	12.1	3.9
26	337	.570	309	.743	13.9	11.7
27	313	.590	296	.775	14.17	15.6

TABLE 9 (cont'd)

Cell #	I_{sc} (mA)	V_{oc} (V)	I_p (mA)	FF	Eff. (%)	τ_{ocd} (usec)
28	317	.583	296	.774	14.0	14.0
29	316	.581	292	.745	13.3	11.7
30	317	.577	294	.744	13.3	11.1
31	297	.534	280	.789	12.2	3.9
32	302	.532	284	.788	12.3	3.3
33	301	.542	285	.795	12.6	1.3
34	300	.551	277	.746	12.0	5.2
35	315	.560	290	.738	12.7	5.3
36	304	.562	281	.758	12.6	4.6
37	301	.573	278	.760	12.8	17.5
38	300	.558	277	.750	12.3	6.5
39	306	.541	287	.779	12.6	3.3
40	302	.541	284	.785	12.5	3.9
41	314	.566	293	.768	13.3	2.6
42	306	.542	284	.749	12.1	7.8
43	293	.561	273	.755	12.3	2.4
44	303	.575	282	.768	13.0	22.1
45	309	.575	287	.761	13.2	21.0
46	300	.530	280	.775	12.0	2.6
47	307	.578	282	.743	12.9	10.4
48	311	.544	289	.731	12.1	.52
49	306	.583	284	.770	13.4	18.2
50	313	.574	289	.759	13.3	18.2
51	308	.548	286	.753	12.4	9.1
52	314	.550	292	.753	12.7	9.1
53	317	.571	295	.756	13.3	13.0
54	318	.535	296	.764	12.7	6.5

TABLE 9 (cont'd)

Cell #	I_{sc} (mA)	V_{oc} (V)	I_p (mA)	FF	Eff. (%)	τ_{oed} (μ sec)
55	320	.565	294	.763	13.4	23.4
56	317	.537	294	.740	12.3	6.5
57	323	.577	300	.759	13.8	13.0
58	317	.583	292	.758	13.7	19.5
59	322	.586	299	.770	14.2	23.0
60	309	.572	285	.748	12.9	11.0
61	300	.542	279	.758	12.0	2.0
62	313	.532	295	.771	12.5	4.6
63	313	.537	293	.758	12.4	3.9
64	313	.537	294	.758	12.4	3.6
65	302	.546	278	.749	12.0	6.5
66	315	.550	291	.749	12.7	7.8
67	318	.551	292	.737	12.6	9.8
68	313	.534	289	.746	12.2	7.5
69	318	.552	294	.737	12.6	9.1
70	315	.550	292	.745	12.6	9.8
71	312	.562	291	.754	12.9	7.8
72	309	.551	290	.768	12.8	7.8
73	321	.556	300	.759	13.2	11.1
74	322	.550	298	.743	12.8	12.8
75	327	.561	299	.733	13.1	13.1
76	318	.538	294	.753	12.55	6.5
77	335	.560	305	.731	13.4	14.3
78	330	.552	303	.741	13.2	10.4
79	327	.540	303	.746	12.8	5.2
80	316	.531	289	.739	12.1	2.6
81	320	.552	299	.762	13.1	4.6

Since the next step was to place the glass plate^{*} on top of the Al plate with more silicone, care was taken to use an excess amount so that the weight of the glass would not crack the cells partially above the Al plate. This was not completely successful and during the final curing stage (glass + Al) three of the cells were fractured. Since all cells were series connected, this reduced the total current and therefore the module efficiency. The measured parameters (AM1) of the module were:

I_{sc} (mA)	- 250
V_{oc} (V)	- 40.6
FF	- .707
η (%)	- 8.8

The area used in the calculation was the area of the Al plate; i.e., 834.6 cm².

It should be noted that the multiple interconnection scheme on our mask was of benefit here. One of the cells was fractured so that if only a single contact were made, the cell fracture would cause an open circuit, and completely disable the module. The fact that the efficiency only dropped ~ 25% indicates the redundancy in the interconnections was a good design feature.

Figure 4 is a photograph of this module.

* ASG Industries - "Sunadex" type

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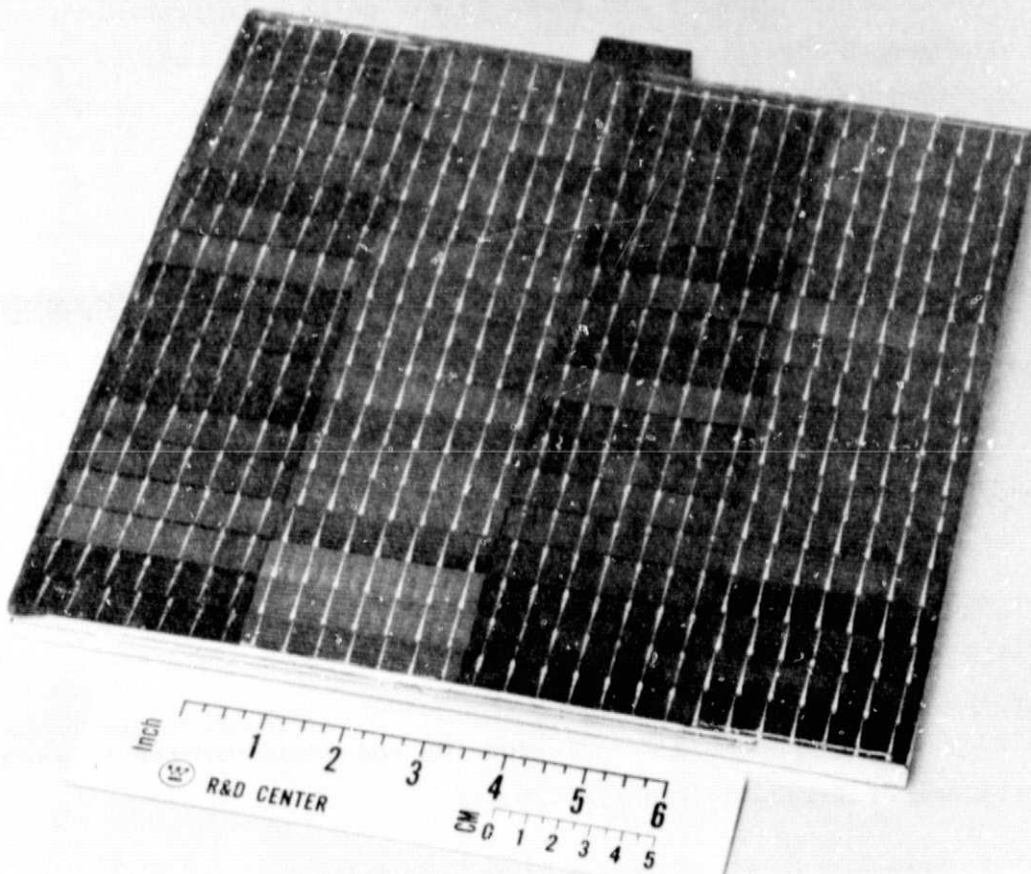


Figure 4. Demonstration Module.

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This module was examined by laser scanning. With this technique, the broken cell appears brighter than other cells due to the higher current density. Thus this cell would be a current limiting factor in the module. The other two broken cells do not show this higher current density, indicating that they are probably only cracked and not completely fractured. Figure 5 shows a photograph of the laser scan.*

The module was also examined with a Barnes-Bofors IR camera. With the module producing 3 watts (electrical forward bias applied), the one broken cell showed only a 0.05°C temperature rise over the other cells. This technique is not sufficiently sensitive for further analysis of the module.

An attempt to repair the module was made. A small portion of the Al plate was milled out directly in back of the broken cell, and the encapsulant was removed, exposing the back of the cell. A copper strap was soldered across the crack of the cell, essentially connecting the two pieces together. After this repair, the module was remeasured both at the Westinghouse R&D Center and at the NASA, Lewis Research Center.** The Westinghouse data is shown in Fig. 6. The efficiency after repair was 11.5%.

3.5 Cost Analysis

A cost analysis of the process sequence was carried on throughout the contract. Initially, the IPEG methodology was used on the processing of continuous lengths of dendritic web. Later in the program a parallel processing of long lengths (~ 3 meters) of web was considered, using both the IPEG and SAMICS models.

* We wish to thank Dr. T. W. O'Keeffe for this data.

** We wish to thank Dr. H. Branhorst and his group for these measurements.

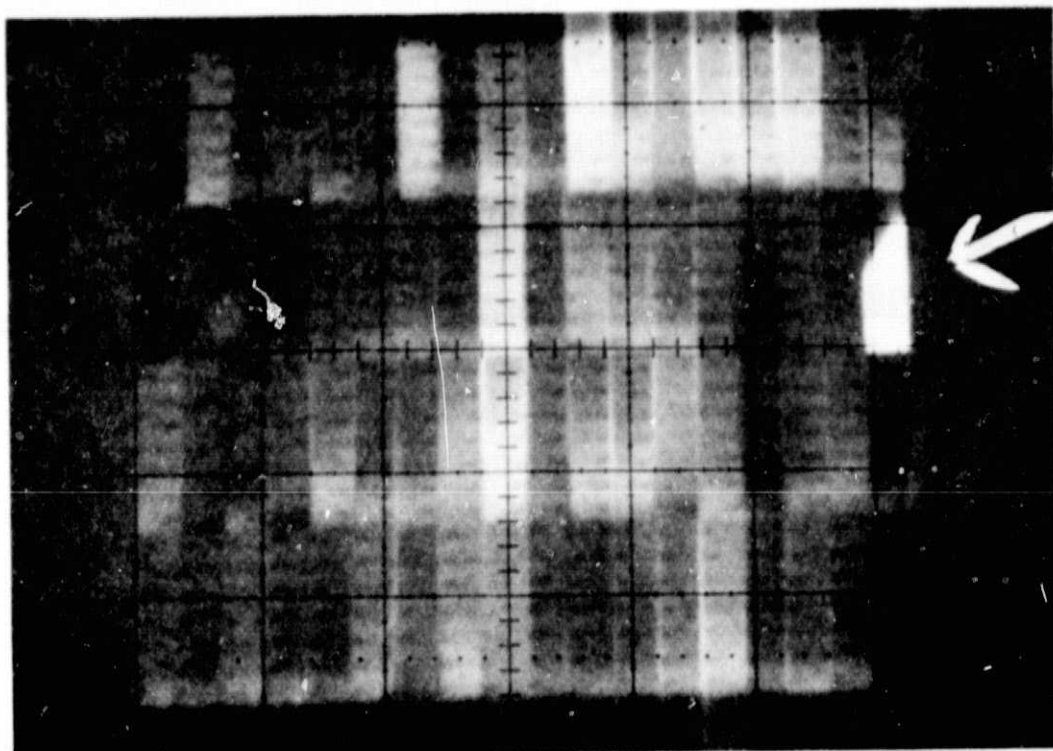


Figure 5. Laser Scan of Demonstration Module. Arrow shows position of broken cell.

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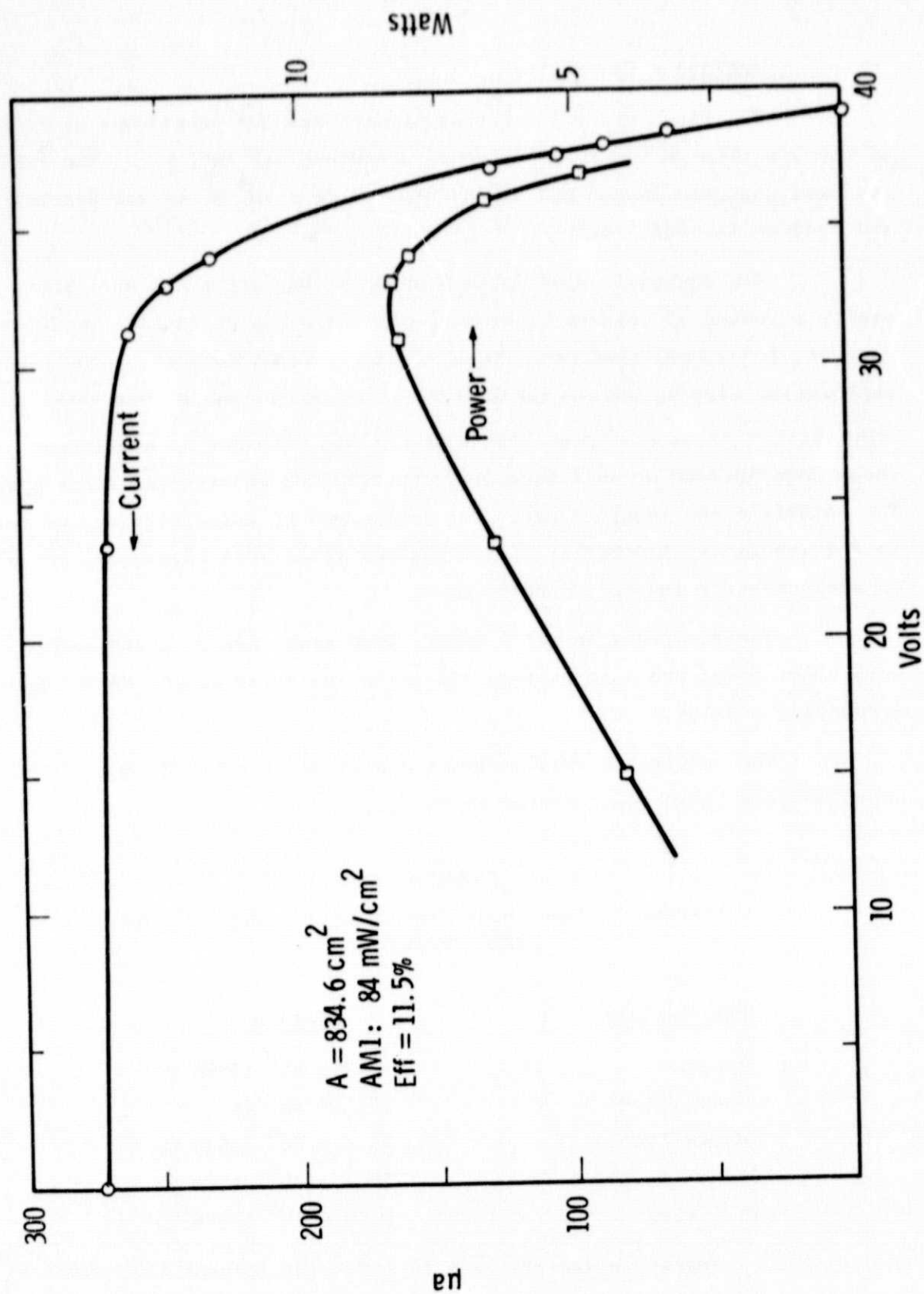


Fig. 6 — Properties of repaired module

Continuous Processing

The first process sequence studied was the continuous processing of the web through the ARRAY sequence discussed earlier. The equipment was designed to process 200 MW/year ($1.82 \times 10^4 \text{ M}^2$ of web per year) and produce 11% modules.

The equipment descriptions used in the Format A's were generally a scaled up version of conventional existing processing machines. However, in several processes, such as, antireflection coating and photoresist dipping and encapsulation, a conceptual design was used. Input from various equipment manufacturers was obtained to supplement these descriptions as well as provide information on required floor space. The materials and supplies usage was determined by extrapolating the usage in the laboratory processes. Labor and utilities were estimated, based on semiconductor industry experience.

These various Format A inputs were transferred to the company work sheet using the cost factors and inflation rates of the SAMICS Cost Accounting catalog.

The results of this analysis are given in Table 10 below. The overall yield factor was assumed to be 93%.

TABLE 10
Cost Analysis - Continuous Processing of Long Lengths of Web
(200 MW/YR)

<u>Cost Factors</u>	<u>Totals</u>
Equipment	47.7×10^6 (1986 \$)
Floor Space	37,200 sq. ft.
Direct Labor	15.4×10^6 (1986 \$)
Direct Supplies	59.7×10^6 (1986 \$)
Utilities	0.49×10^6 (1986 \$)

Selling price per watt in 1986 - \$0.35/peak watt (1975 \$)

The selling price does not include the cost of the input Si web. This cost is targeted to be \$0.17/peak/watt (1975 \$) in 1986. Thus the total cost in 1986 (1975 \$) would be \$0.52/peak watt.

A detailed study of the process costs shows that the largest single material cost is the silane (\$183.40/lb in 1975 \$) used in the junction formation step. This cost is ~ 25% of the total. Other cost drivers are materials for encapsulation (mainly glass and backing board) and equipment for the metallization process. These data indicate where effort must be put to reduce the overall cost.

Continuous Processing of Finite Lengths of Web

In a production situation, it may be advantageous to process shorter lengths of web. Therefore, we have designed a process sequence that has an input of 50 three meter lengths of web which are processed in parallel.

The factory using this process sequence consists of eight parallel lines each capable of producing 25 MW per year, with the total factory producing 200 MW per year. The sequence is divided into five major processes with a total of 44 sub-processes. An outline of this conceptual factory with all the processes was described in the Annual Report, together with the labor, capital, commodities and utilities required by the Format A's.

The input to this sequence is 50 strips of web, each 5 cm wide between dendrites and 3 meters long. These web strips are held flat in a tray, and proceed through most of the processing steps in the tray. The processing equipment is envisioned to accept these trays of webs and the trays themselves are considered to be strong so that little breakage of the web can occur. In addition, they will be lightweight and have a small surface area so that they do not interfere with the process. The factory module processes $5000 \text{ cm}^2/\text{min}$ of web.

The required inputs were transferred from the Format A's to the SAMIS program. Regarding these inputs several features should be noted about the commodities. First we assumed a cost of silicon web input at \$0.17/watt (1975 \$); this price is one of the goals of the LSA project. Second, we assumed a cost of \$50/lb for silane (1986 \$). We feel that this price is justifiable (compared to the SAMICS cost account catalog price of ~ \$183/lb) since the manufacturers of polycrystalline silicon will be on a stream in 1986 and depending on the process silane should be in copious supply. Other cost inputs not in the cost account catalog were derived from vendor catalog prices. The analysis shows that using this process and the conceptual factory at 1986 selling price (in 1975 \$) of \$0.56 is obtained. This includes the cost of the silicon web at \$0.17/watt (1975 \$).

Figure 7 shows a bar chart of the costs involved in the process. The processes and materials which have a significant effect on the cost are the web itself and the encapsulating materials. Replacement of Ag with Cu would save almost \$0.01/watt. This chart also shows that the design and building of the capital equipment used in processing must be carefully considered since this is the major controllable cost driver.

Pilot Line

The input data used in the continuous processing lengths of web was revised and recalculated to determine the cost of the solar cell modules produced in a conceptual pilot line. The following assumptions were made:

- . 2 MW/yr productions - $2 \times 10^4 \text{ M}^2/\text{yr}$ for 10% module
- . Capital costs = capital cost of a 25 MW module + 20%
- . Labor = $\frac{1}{2}$ of a 25 MW module
- . Materials and utilities = $\frac{2}{25}$ of a 25 MW module
- . Operation in 1983
- . Floor space = same as that of a 25 MW module

For this process under these conditions, the selling price in 1984 would be \$1.40/peak watt (1975 \$).

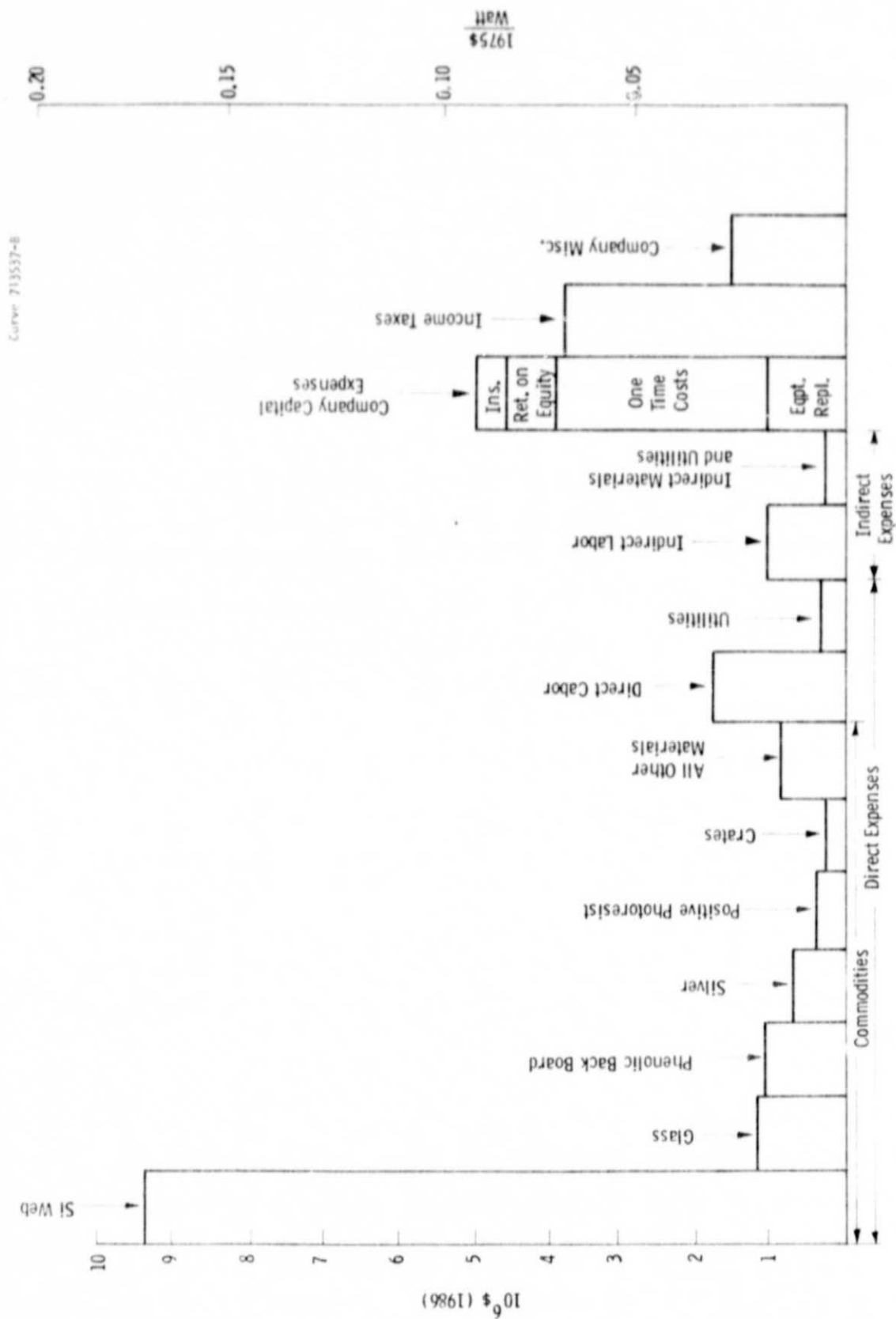


Fig. 7 Breakdown of 25 MW/year Processing Line
(Total 1986 \$ and 1975 \$/peak watt)

4. CONCLUSIONS

- Among all the metal systems tested, only Ti Pd Ag appears to have the required long term stability characteristic at the present time.
- The formation of deep, Al doped, BSF region with a V_{oc} of 0.59V is feasible using alloying techniques.
- Various metal foils (Cu, Ag plated Cu, Al) can be ultrasonically welded to solar cell contact systems presently in use.
- Based on results with a demonstration module ($\approx 800 \text{ cm}^2$), it appears that modules using dendritic web silicon solar cells can be fabricated with efficiencies in excess of 12%.
- A selling price near \$0.50/watt peak for solar cell modules. (1986 price in 1975 dollars) appears feasible.

5. PROGRAM STATUS

5.1 Present Status

The work funded under unilateral modification #3 is essentially on schedule. Substantial progress has been made on alloyed Al back surface field with p^+ region penetration up to 10 μm and V_{oc} of 0.59V. The use of ultrasonic welding techniques for interconnecting cells has been shown feasible, and initial welding parameters established. The demonstration module with broken cells was repaired and the efficiency increased from 8.8% to 11.5%.

5.2 Future Work

During the next quarter work will concentrate on determining the feasibility of plasma etching, and further studies of Al BSF structures. In addition, spray techniques for applying an anti-reflective coating will be studied.

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